

SnAgCu Solder Interconnection Behaviour under Gamma Radiation Exposure

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Abstract. Radiation particles with enough energy to break the chemical bonds of the materials, such as gamma radiation, may affect the performance of the device. In this research, the physical, mechanical properties and microstructure evolution of lead-free solder joints radiated with gamma radiation were investigated. Prior to characterization, the solder paste of tin-silver copper (SnAg₃Cu_{0.5}; SAC305) was manually deposited on the printed circuit board using a stencil printing method and reflow soldering process. Subsequently, the solder was exposed to gamma radiation. As the gamma radiation dose increased, the thickness of the intermetallic compound (IMC) layer of the solder increased, and the contact angle remained to have good wettability. The nanoindentation test revealed the occurrence of pop-in events due to the atomic distortion and dislocation density of the SAC305 samples. The hardness and reduced modulus values increased up to 500 Gy owing to the disturbance in the atomic arrangement of the solder material. However, the values decreased as the radiation dose increased (5000 Gy) which could be linked to the presence of voids and heterogenous IMC. The eutectic phase area showed a parallel trend to the hardness value obtained. Field Emission Scanning Electron Microscopy and Energy Dispersive Spectroscopy analysis found that Cu₆Sn₅ and Ag₃Sn compounds dominated the intermetallic layer in the Sn matrix. It is believed that heat released by gamma radiation changed the nature of solder materials from elastic to plastic as well as coarsen the microstructure and increased the IMC thickness. Therefore, the effect of radiation on microstructural properties of solder should be considered when used in radiation-related applications.

INTRODUCTION

Soldering, which is an integral part of the integrated circuits (IC) manufacturing process, supports the bonding of electrical conduction in integrated circuits between electrical components and printed circuit boards [1]. Electronic devices are commonly used in all facets of technology in this modern day and are most usually found in domestic products such as cell phones, personal computers, storage devices, and other daily use devices. The solder joints that link electronic components provide the backbone of an electronic system, acting as both electrical connections and mechanical support between the components and the board [2].

Along with concurrent progress, the manufacturer of electronic devices with multifunctional characteristics has driven electronic packing to increase its density throughout time. Due to technological advancement, solder junctions

are continually reducing to a much smaller scale. In particular, the solder volume per junction of standard surface mount technology (SMT), which is approximately 0.01 to 1 mm³, has been decreased to 10⁻⁴ ~ 10⁻⁵ mm³ in modern fine-pitch assembly [3][4]. Solder joint size reduction has a substantial impact on the interfacial interaction of intermetallic compound (IMC) layer development and the progression of the solder matrix's microstructure [5]. According to Jeon et al. [6], the solder joint is subjected to a high heat density, which causes the IMC layer to expand, causing the joints to crack. As a result, the solder joint's reliability is jeopardized, especially in extreme settings. Furthermore, higher thermal coarsens the solder matrix's microstructure particle sizes and interfacial phase. Thus, the solder matrix might be softened, resulting in further deterioration in the hardness properties of the solder [7].

Traditional tin-based solder systems have been phased out of electronic manufacturing in order to lessen the toxicity and dangerous consequences caused by the use of lead as a soldering metal. Tin-silver-copper (Sn-Ag-Cu, SAC) solder alloys have been evaluated as a promising candidate for joining interconnections on Cu substrates in electronics assembly after significant investigation. Several SAC solder alloy series are currently being produced and explored, including SAC305, SAC0307, SAC387, and SAC396. [7].

Gamma radiation was employed as a technique in this research to investigate its effects on solder joint reliability. The influence of ionising radiation, specifically gamma radiation, has generated curiosity, particularly in terms of the durability of electronic materials under extreme temperatures, as it can cause the atoms of one substance to become ionised or charged. According to Vaiserman *et al.* [8], exposure to natural and man-made radiation sources can occur on a regular basis, particularly in research facilities and medical institutes. Radiation's major effects on matter can be classified into three categories: atomic displacement, impurity generation, and ionization [9]. The effect of gamma radiation on materials has sparked significant interest and prompted the creation of innovative materials with high gamma radiation resistance. The irradiated solder junction may have performed poorly due to gamma radiation-induced changes in its mechanical and microstructure properties. Wang *et al.* [2] found that energetic electrons produced by gamma radiation altered the morphology of the IMC layer and caused microscopic flaws in the characteristics of SnPb solder connections. This raises serious concerns about the micromechanical alterations and functionality of solder material as a result of being exposed to gamma radiation. Thus, this paper aimed to explore the correlation between the hardness, intermetallic compound (IMC) and eutectic phase area under low gamma radiation exposure.

Methodology

The lead-free solder pastes of SnAg₃Cu_{0.5} (SAC305) supplied by the Red Ring Solder (Malaysia) Sdn. Bhd. was prepared by manually deposited onto the printed circuit board (PCB) using stencil printing to form a solder joint. Prior to irradiation using gamma radiation, the samples went through reflow soldering at 260 °C of the maximum temperature. An industrial Excel 220 Gamma Cell irradiator with a Cobalt-60 source was used to irradiate the samples at 5, 10, 15, 20, and 25 Gy, with an operating dosage of 0.93 kGy/h. For evaluating mechanical behavior using nanoindentation analysis, the samples were metallographically prepared that including mounting, grinding, polishing and etching. The samples were cold mounted with epoxy, then polished with DP Nap polishing cloth and liquid lubricant of 1 and 0.25 μm diamond spray. The samples were etched (5 % hydrochloric acid and 95 % methanol) and examined under an optical microscope for microstructural examination, including evaluation of IMC growth on soldered samples. Average IMC thickness was investigated using ImageJ software where the total thickness was divided by 100 [10]. In addition, the measurement of the eutectic phase area was calculated using ImageJ software by determining its thresholding. Afterward, the indentation was conducted at the center of the solder joint with three-sided pyramidal Berkovich tip using a Bruker-Hysitron TI950 Triboindenter. During the indentation, the loading rate was kept constant at 0.5 mN/s to the solder surface, achieving a maximum load of 10 mN and remaining for 10 s until unloading. The nanoindentation data attained was analyzed using the Oliver and Pharr method [11] that corresponded to hardness of the solder samples.

Results and Discussion

In this study, the microstructural evolution of SAC305 exposed to various doses of gamma radiation was conducted. An optical microscope was used to examine the microstructure of the control and radiated SAC305 samples, and ImageJ software was used to calculate the IMC thickness and eutectic phase area. The IMC thickness, eutectic phase area and hardness of SAC305 were tabulated in Table 1. Figure 1 is a micrograph of SAC305 solder IMC thickness. The micrograph demonstrated that throughout the soldering, Sn atoms from the solder alloy interacted with molten substrate elements to form the interfacial layer between the solder alloy and the substrate. The IMC thickness of the tested solders increased with increasing radiation exposure, suggesting that gamma radiation could influence the morphologies of SAC305 solder, leads to a change in IMC thickness. The formation of a scallop-type morphology is one of the features of the IMC. The scallop is a typical development form that often grows larger but fewer as time passes. In the control sample, the IMC produced between solder and the Cu substrate appeared thin and developed a scallop-like structure. Nevertheless, after irradiation, the interface became uneven, indicating the development of several outshoots inclining away from the substrate pad. The outshoots grew in size with the increment of radiation dose, causing changes in the IMC thickness.

The heat produced by the gamma was expected to play a role in the development of IMC formation. The development of Cu_6Sn_5 IMC, which was stimulated by the aid of heat during the irradiation, caused the increase in IMC layer thickness. The Cu_6Sn_5 IMC layer was created by facilitating the diffusion of Sn and Cu atoms from either the bulk solder and substrate using heat and high pressure [7]. IMC growth was regarded as a common diffusion growth that should be restricted by interdiffusion of substrate and solder components [12].

Table 1 Hardness, average IMC thickness and eutectic phase are of SAC305 solder

Sample (Gy)	IMC Thickness (μm)	Eutectic phase area (%)	Hardness (GPa)
Control	4.97	20.28	0.26
5	5.24	24.16	0.28
10	6.53	27.30	0.36
15	6.56	29.65	0.37
20	6.80	25.34	0.30
25	6.83	23.74	0.23

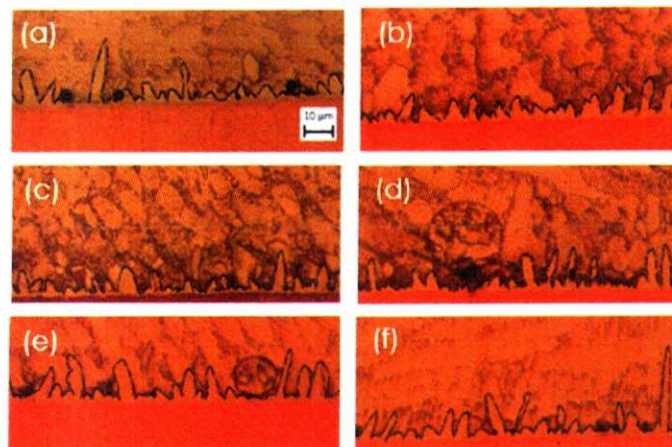


Figure 1: IMC of (a) control SAC305, (b) 5 Gy, (c) 10 Gy, (d) 15 Gy, (e) 20 Gy, and (f) 25 Gy

Figure 2 shows the microstructure of SAC lead-free solder was consist of primary β -Sn, platelet-type Ag_3Sn , and scallop-like Cu_6Sn_5 . The element found is as established in previous literatures [13][15]. The phase distribution of the eutectic in the SAC305 solder was altered by different dosages of gamma radiation. For the controlled sample, the eutectic phase area calculated was 20.2 % and kept increasing up to 15 Gy. However, from 20 to 25 Gy, the area

decreased to 17.66 % as the exposure dose increased. According to El-Daly *et al.* [14], the heat generated by gamma rays resulted in a coarsening behaviour of the microstructure and IMC in the solder. According to Table 1, the eutectic phase area for the SAC solder showed comparable values to the hardness obtained which based on our previous study [15].

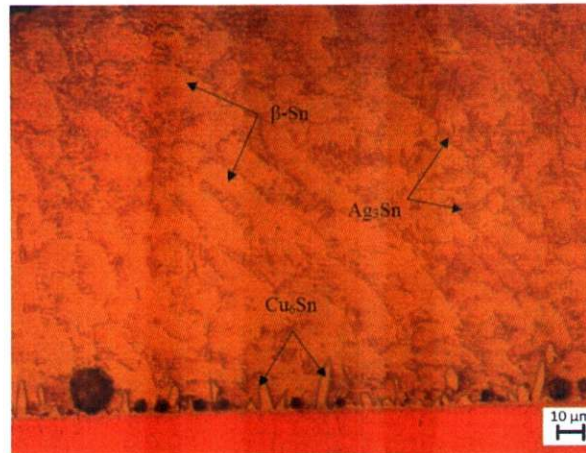


Figure 2: Microstructure of control SAC305 solder

Figure 3 shows the micrograph of SAC305 after etching process, revealing the eutectic phase area of the solder. By using ImageJ, the eutectic phase area was analysis and tabulated in Table 1. The presence of the eutectic area was able to prevent the dislocation occurrence. Force is exerted to the solder surface during the indentation. The greater the eutectic area, the more likely the indenter will be unable to penetrate deeper into the solder, increasing the hardness of the samples. The continuous movement of dislocations facilitates deformation, which contributes to the reduced hardness properties [16]. Tan *et al.* [17] proposed the presence of β -Sn phase and the production of Cu_6Sn_5 whiskers in the eutectic region lowered the impedance of the solder matrix to indentation force, resulting in a decreased in hardness. The decrease in hardness with increasing grain size is related to $d^{-1/2}$ (where d = average grain diameter), according to the Hall-Petch equation, which discussed the role of grain size in resolving hardness. As a result, the relationship between hardness and eutectic phase area is established.

The strength of the material is the rigidity of the material to the occurrence of plastic deformation owing to applied force and was abnormalities in the area where the indentation originated [18]. The heterogeneities in the sample are one of the variables impacting the diversity in material behavior and hardness. Heat treatments and cold work can produce these variations by changing the elastic and plastic properties of the metal. Heterogeneities in anisotropic metals can also be induced by crystallographic orientations. Gamma radiation causes a coarsening behavior to occur in the solder matrix which then lead to the increment of the IMC and changes in the eutectic phase area. Exposure from 5 to 15 Gy of gamma radiation resulted in increasing the hardness up to 0.37 GPa. This phenomenon could be explained by radiation that induced structural and atomic rearrangements in solder, which affect the hardness and ductility [19]. As radiation dose increases from 20 to 25 Gy, the IMC thickness continue to increase due to more heat generated. However, the value of the eutectic phase area and hardness decreased due to the changes in the morphology of the SAC305 solder. This result was similar in trend the findings of Wen *et al.* [20], who discovered that exposure up to 1000 h of gamma radiation, resulted the reduction in the shear strength of gold-tin (AuSn) solder samples. It can be concluded that exposure to gamma radiation affect the structural and atomic arrangement, resulting in the change of IMC thickness, eutectic phase area and hardness value.

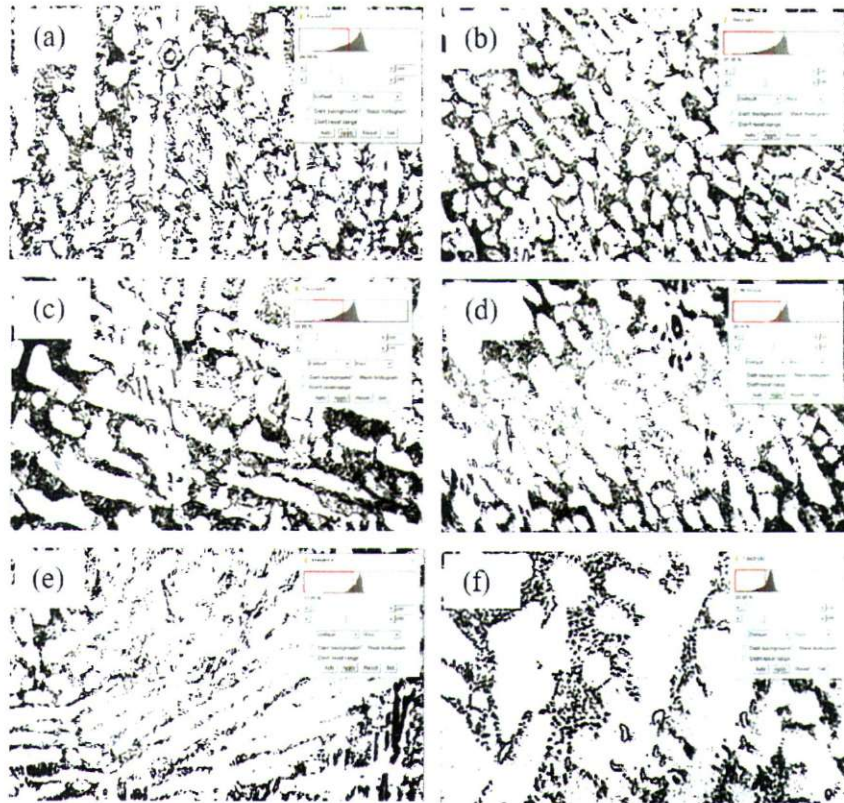


Figure 3: The micrograph of (a) control SAC305, (b) 5 Gy, (c) 10 Gy, (d) 15 Gy, (e) 20 Gy, and (f) 25 Gy after etching

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Conclusion

The correlation of hardness, IMC, and eutectic phase area under low gamma radiation exposure on the SAC305 solder was successfully investigated via nanoindentation and optical microscope. Due to variances in the microstructure of soldered samples, gamma radiation caused major adjustment in hardness, IMC thickness, and eutectic phase area. As radiation dose increased from 5 to 15 Gy, the hardness of the sample increased to 0.37 GPa and decreased to 0.27 GPa when radiated with higher dose. This phenomenon was attributed to the structural and atomic rearrangement of solder. However, at higher dose, the gamma radiation caused the microstructure of the radiated solder became unstable thus increased the thickness of IMC between the solder and the Cu substrate.

Remarkably, the exposure to different doses of gamma radiation affected the phase distribution of eutectic in the SAC305 solder. The eutectic phase area for the SAC is parallel to the hardness obtained.

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